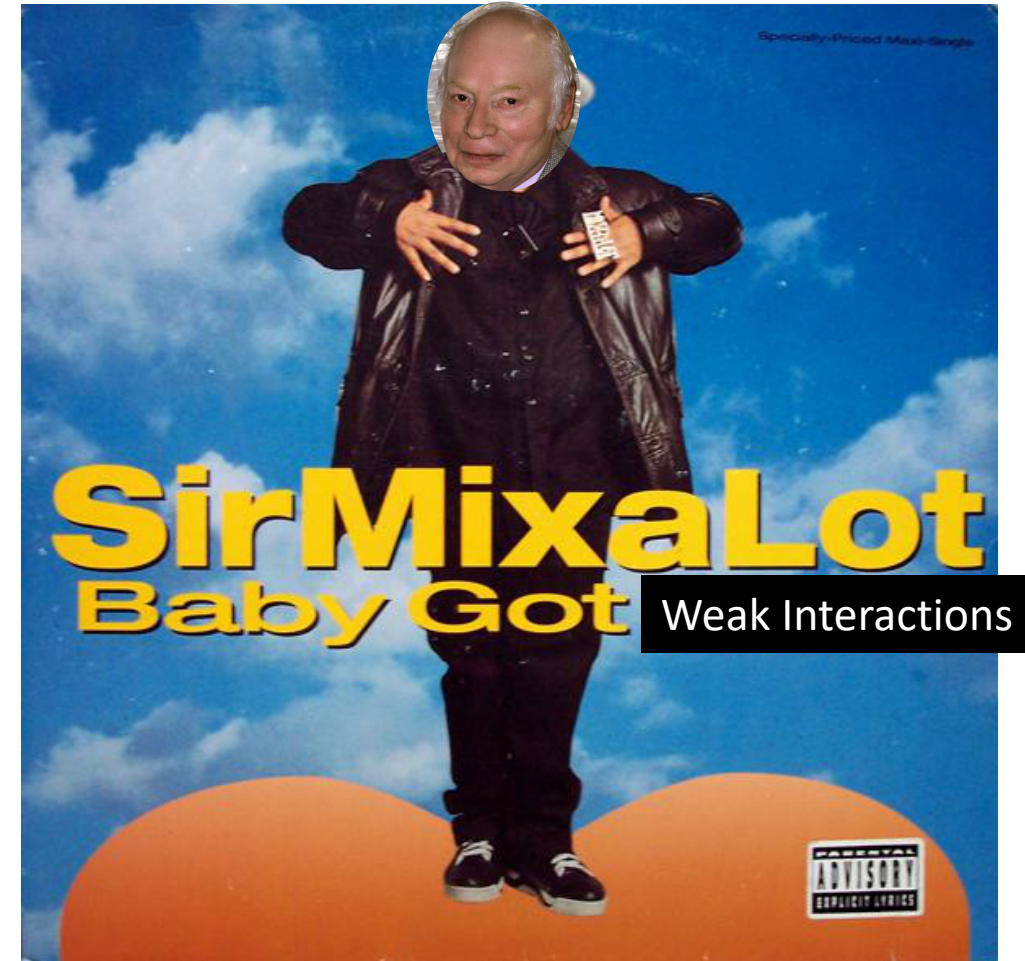


Measuring the Weak Mixing Angle

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October 28, 2020

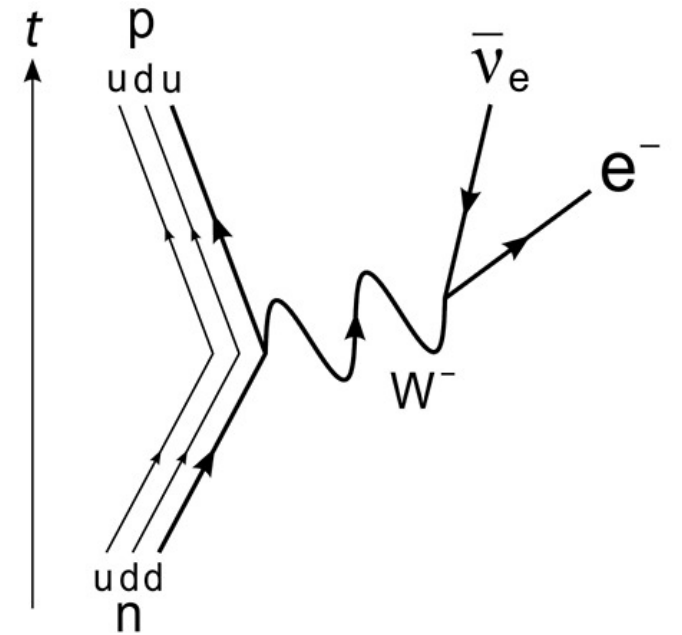
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Part I: Theory and Introduction

Electroweak Physics by Glashow

- “At first sight there may be little or no similarity between electromagnetic effects and the phenomena associated with weak interactions...” – S. Glashow (1961)
- By this point, people had the idea that weak interactions were mediated by charged vector bosons with mass above the K-meson
 - (They weren’t wrong)
- Symmetry up to this point mostly involved particles of similar mass, so the idea that a symmetry related the photon and these massive bosons was odd
 - Regardless, Schwinger had an idea for an “isotopic” triplet which was the photon+ 2 charged massive bosons



Electroweak Physics by Glashow

- Glashow found that this idea was not sufficient
 - If the neutral component in the triplet was the photon, the charged bosons could not have the right CP properties
- He *could* get things to work out right by introducing a new vector boson though
 - So now there is a triplet (2 charged + 1 neutral boson) and a singlet (1 neutral boson)
 - Neither of the neutral bosons could be the photon alone though
- If the neutral bosons are diagonalized into mass states though, you get the photon and a massive neutral boson

$$L_M = \frac{1}{2}M_A^2(Z_\mu^3 \cos \theta' + Z_\mu^S \sin \theta')^2 + \frac{1}{2}M_B^2(Z_\mu^S \cos \theta' - Z_\mu^3 \sin \theta')^2,$$

in which the fields

$$A_\mu = Z_\mu^3 \cos \theta' + Z_\mu^S \sin \theta', \quad B_\mu = Z_\mu^S \cos \theta' - Z_\mu^3 \sin \theta' \quad (4.7)$$

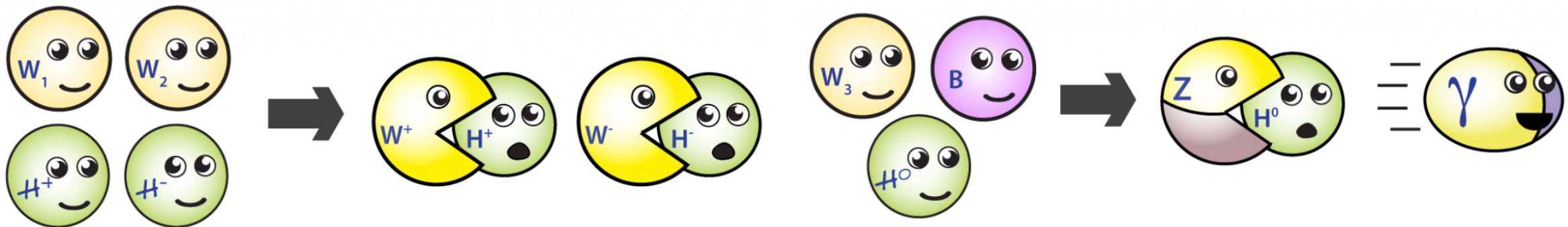
describe spin-one particles with masses M_A and M_B .

- He didn't say it explicitly, but this is our familiar SU(2)xU(1)
 - Just with no Higgs mechanism yet
- (As a side note, this paper was basically totally ignored for 6 years)

Just to be clear,
that's the weak
mixing angle

Electroweak Physics by Weinberg

- Fast forward to 1967
- Weinberg introduces an $SU(2) \times U(1)$ theory with a Higgs mechanism to generate massive bosons
 - “A model similar to ours was discussed by S. Glashow... the chief difference is that Glashow introduces symmetry-breaking terms into the Lagrangian, and therefore gets less definite predictions.”



Electroweak Physics by Weinberg

- Weinberg introduced the Electroweak Lagrangian basically as we have it today (written in a more modern form here):

$$\mathcal{L} = -\frac{1}{4}(W_{\mu\nu}^a)^2 - \frac{1}{4}B_{\mu\nu}^2 + (D_\mu H)^\dagger (D_\mu H) + m^2 H^\dagger H - \lambda(H^\dagger H)^2$$

With

$$D_\mu H = \partial_\mu H - igW_\mu^a \tau^a H - \frac{1}{2}ig'B_\mu H$$

And remember

$$Z_\mu \equiv \cos \theta_w W_\mu^3 - \sin \theta_w B_\mu$$

$$A_\mu \equiv \sin \theta_w W_\mu^3 + \cos \theta_w B_\mu$$

- Note that there are 4 parameters: g , g' , m , and λ
 - m and λ get folded into Higgs vev: $v = \frac{m}{\sqrt{\lambda}}$

Electroweak Physics- real parameters

- There are many ways to express and re-express these parameters in terms of more “physical” parameters
 - $e = g \sin \theta_w = g' \cos \theta_w = \frac{gg'}{(g^2 + g'^2)^{1/2}}$ (note: $\tan \theta_w = \frac{g'}{g}$)
 - $m_W = \frac{v}{2} g$
 - $m_Z = \frac{1}{2 \cos \theta_w} g v = \frac{m_W}{\cos \theta_w} = \frac{1}{2} v \sqrt{g^2 + g'^2}$
 - $\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 M_W^2} = \frac{1}{2 v^2}$
- **Important:** if you know g , g' , and v , then you can predict all Electroweak processes
 - Alternatively, you can measure some of the “physical” versions
 - G_F and e were already well measured at this point
 - That means we have to measure m_W , m_Z , or $\sin \theta_w$ somehow
 - It turns out that the bosons were too heavy to measure back then, so we’ll have to do $\sin \theta_w$

Now, how do we do that measurement?

Part II: Deep Inelastic Neutrino Scattering

Why DINS?

- Fermions couple to the W bosons according to their isotopic charge
 - See table
- Fermions couple to the photon according to their electric charge
 - See table
- Fermions couple to Z bosons according to: $\frac{e}{\sin \theta_w \cos \theta_w} [T_3 - Q \sin^2 \theta_w]$
- So if we measure the couplings of fermions to the bosons, we'll get $\sin \theta_w$

Charge:	Isotopic	Hyper	Electric
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d_L	-1/2	+1/3	-1/3
e_L	-1/2	-1	-1

$(\nu_e)_L$	+1/2	-1	0
u_L	+1/2	-1/3	+2/3

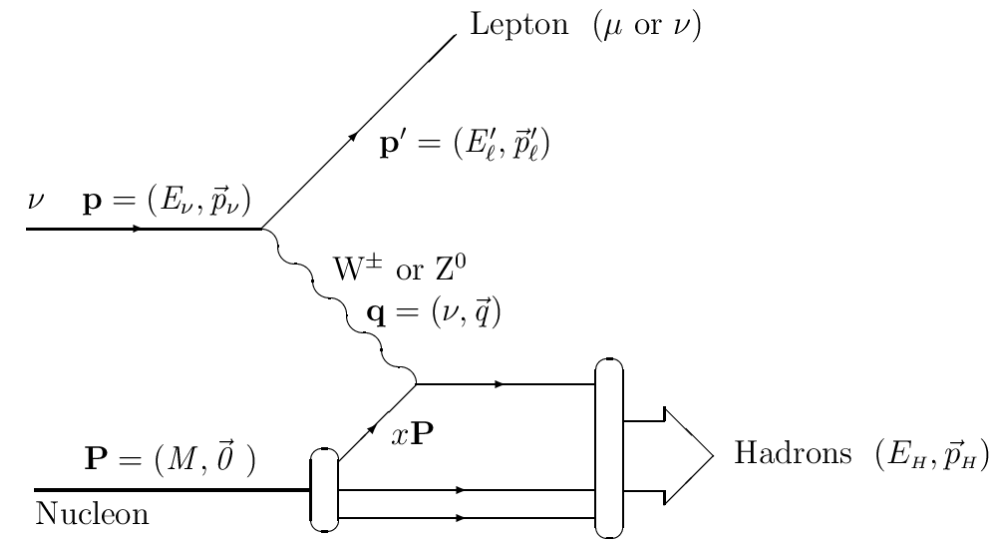
d_R	0	+2/3	-1/3
e_R	0	-2	-1

$(\nu_e)_R$	0	0	0
u_R	0	+4/3	+2/3

(Weak isotopic charge) = (electric charge) - $\frac{1}{2}$ (hypercharge)

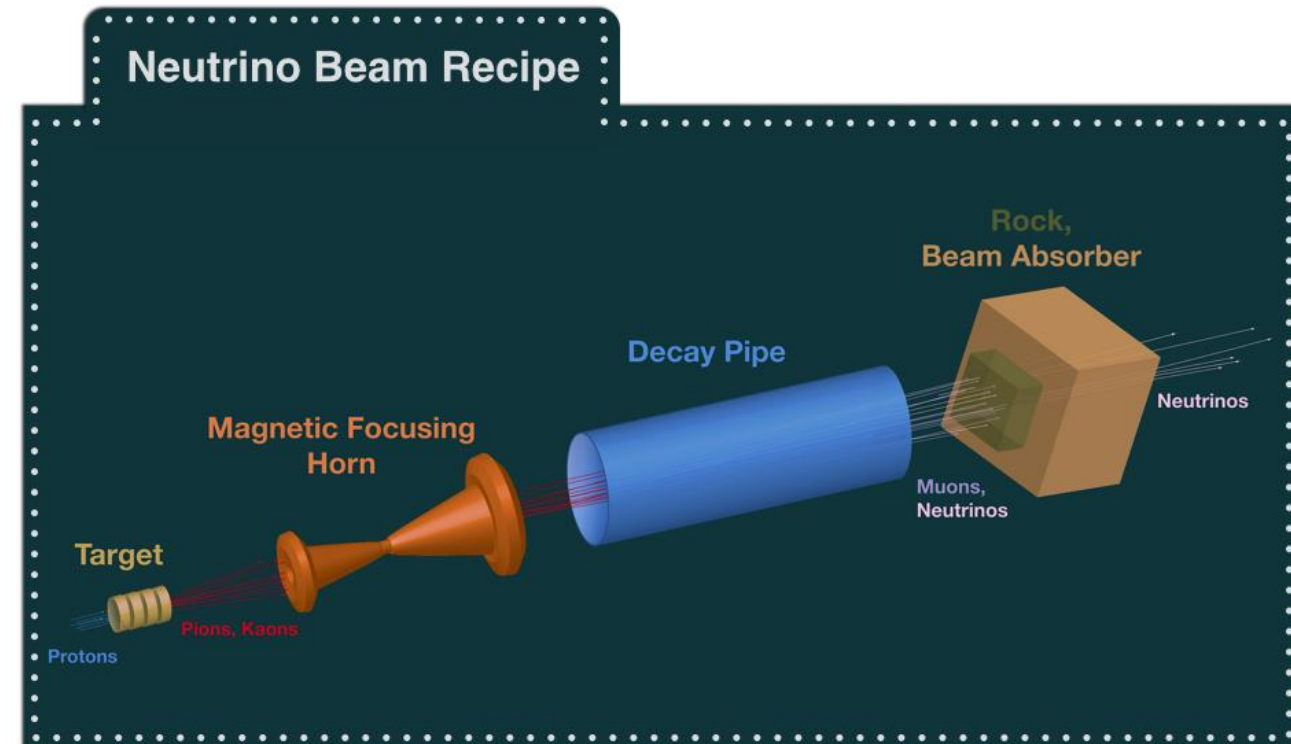
Why DINS?

- That's a little non-trivial
- We'll have to use neutrino and anti-neutrino scattering to try to isolate $\sin \theta_w$
- $R_\nu = \left(\frac{NC}{CC}\right)_\nu = \frac{1}{2} - \sin^2 \theta_w + \frac{20}{27} \sin^4 \theta_w$
- $R_{\bar{\nu}} = \left(\frac{NC}{CC}\right)_{\bar{\nu}} = \frac{1}{2} - \sin^2 \theta_w + \frac{20}{9} \sin^4 \theta_w$
- This is what we actually measure



How do we make a neutrino beam?

1. Smash accelerated proton onto a fixed target, making pions and kaons
2. Focus charged pions and kaons (you can choose their charge at this step)
3. Let those particles pass through a tunnel that's long enough that most of the pions will decay to muons (and muon neutrinos), but most of the muons won't decay to electrons (and electron neutrinos)
4. Use some absorber to block the muons and any remaining pions/kaons. Only the neutrinos will get through!



At CERN 1973

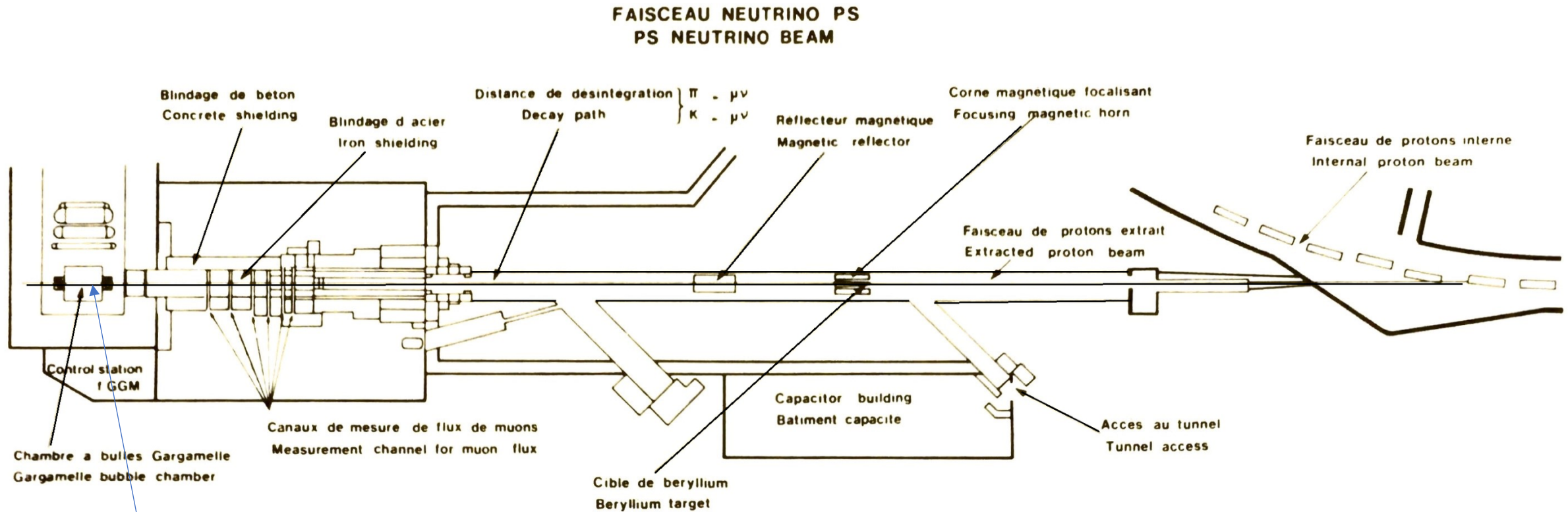


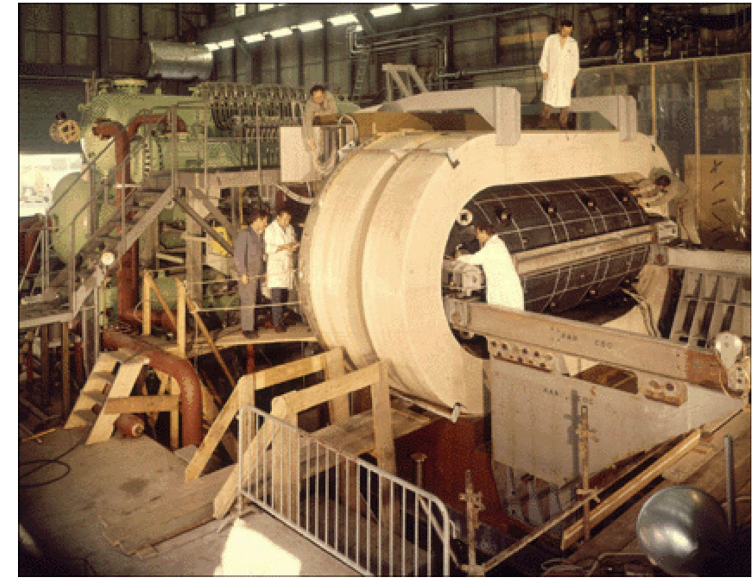
Fig. 1-2. The CERN neutrino beam lay-out.

Neutrinos go into
Gargamelle bubble
chamber over here

Start with protons
over here

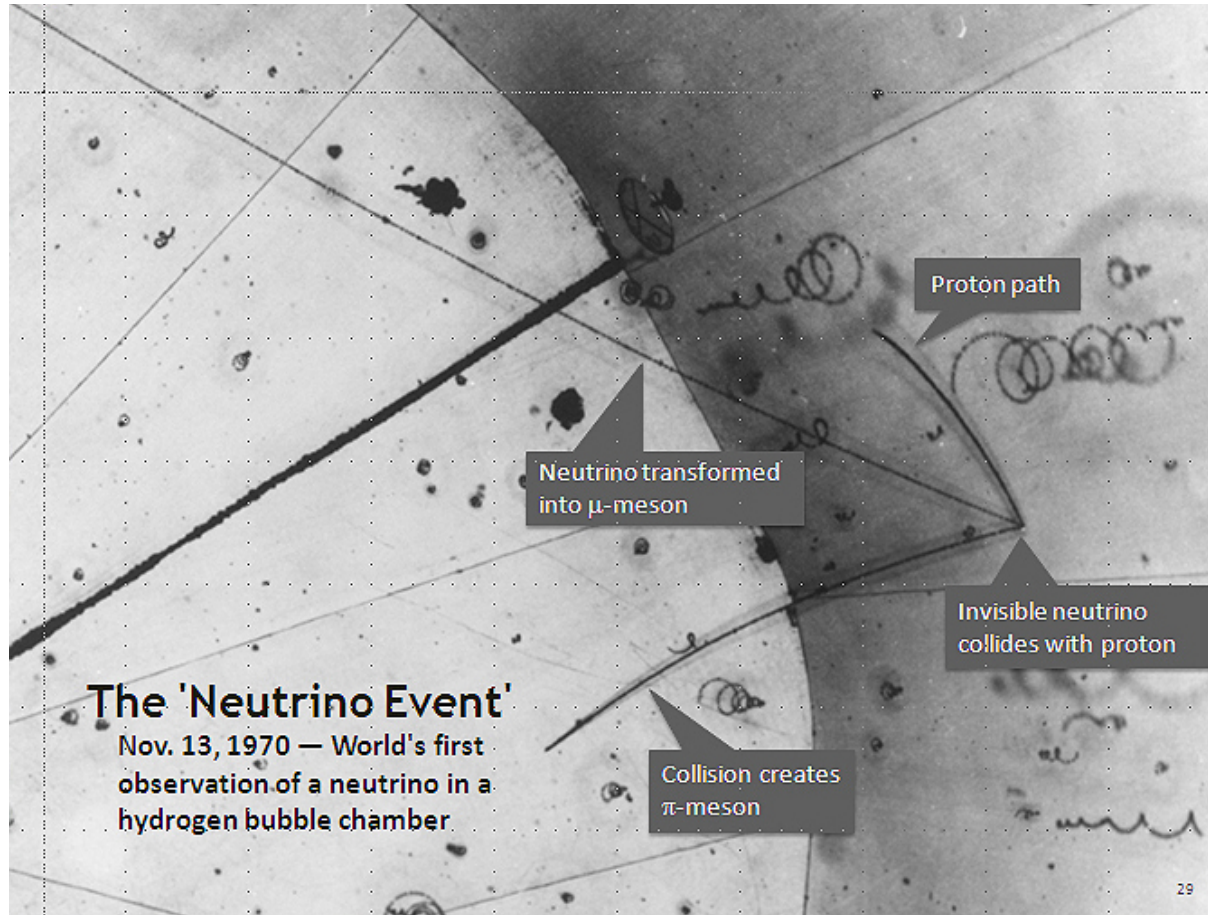
Gargamelle

- Gargamelle was a bubble chamber filled with heavy-liquid Freon
- For a neutral current interaction, you're looking for no incoming particle + splash of hadrons + no outgoing leptons
 - Incoming neutrinos are essentially invisible
- For a charged current interaction, you're looking for no incoming particle + splash of hadrons + 1 outgoing muon



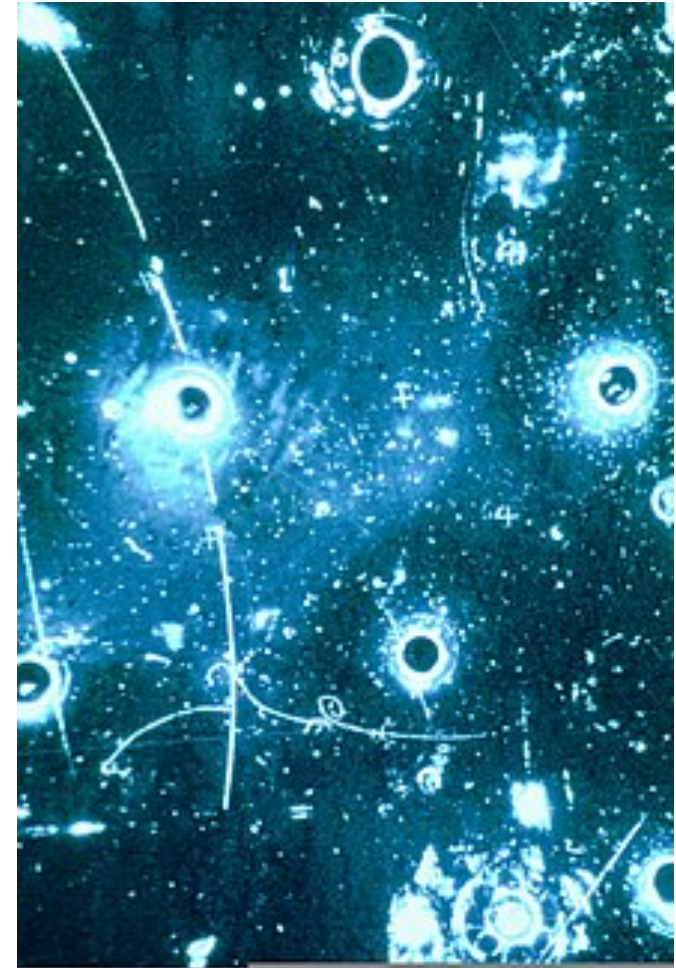
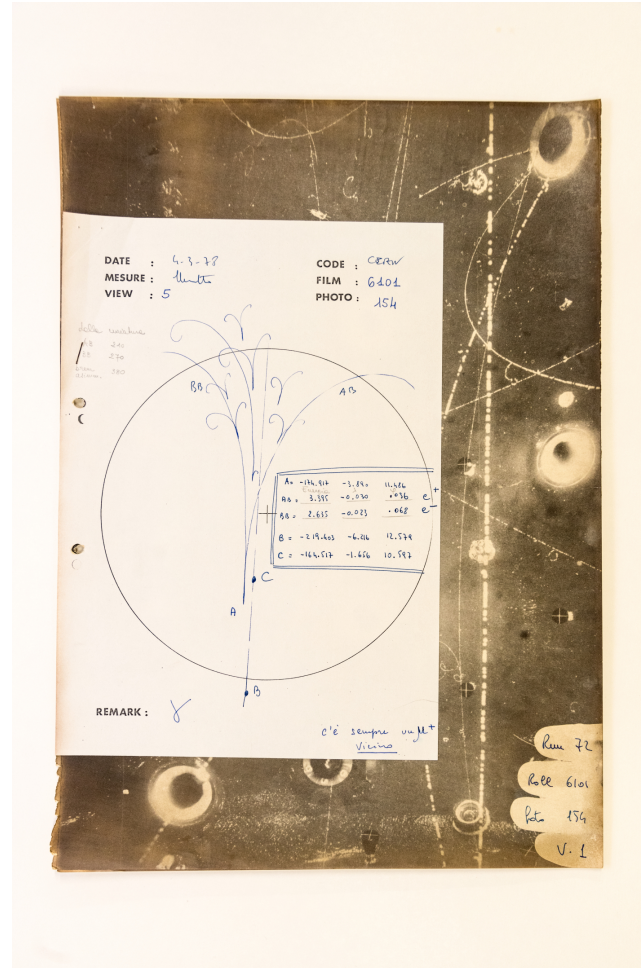
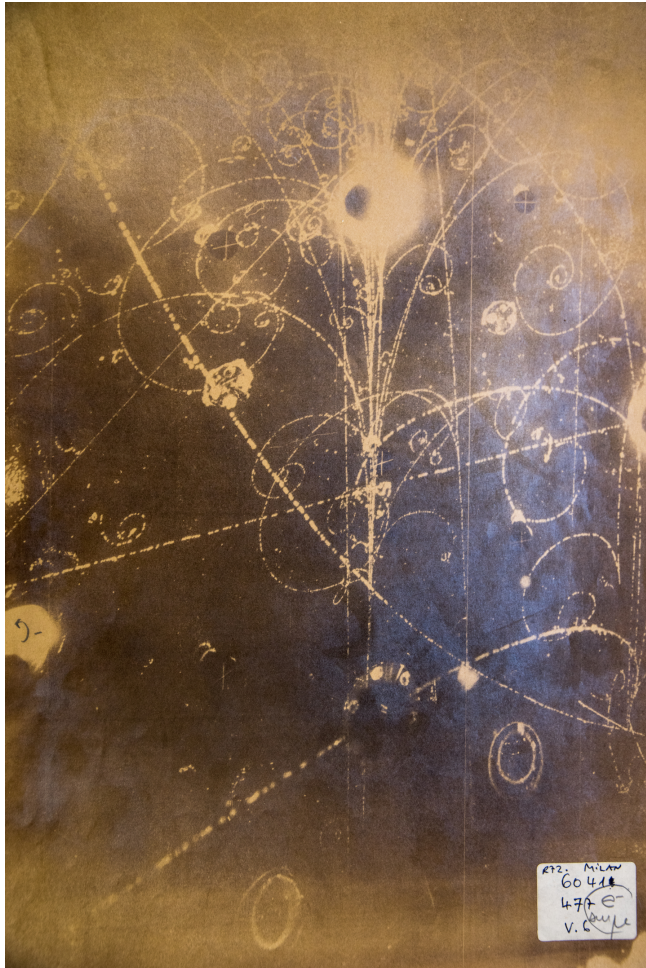
Gargamelle in 1970 (top)
and today (bottom)

Tagging neutrino events



This is not from Gargamelle, but it illustrates the principle of a charged current interaction

Some Gargamelle Pictures



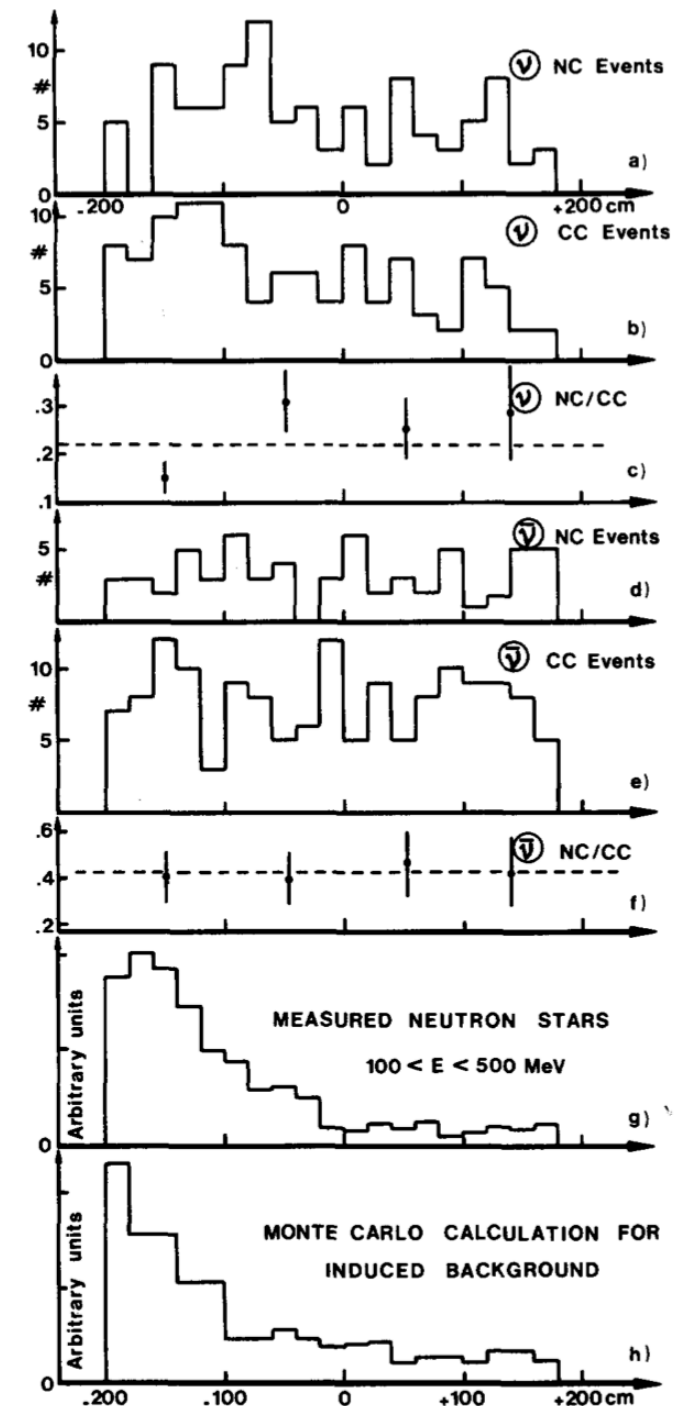
The idea was to have grad students look through thousands of pictures until they found something interesting
Hadrons are tagged by interaction type or by range-momentum and ionisation

Gargamelle 1973

- In 1973, a CERN group measured NC/CC based on 83,000 neutrino pictures and 207,000 antineutrino pictures
- The main background was when a neutrino interacts in the shielding, creating a neutron, which then mimics a neutrino interaction
 - Background estimated by also looking for CC events where a visible neutron star is created- called “associated” or “AS” events
- Cut on hadronic energy > 1 GeV to determine neutral particle direction
- In fiducial region:
 - Neutrino pictures: 102 NC, 428 CC, and 15 AS events
 - Antineutrino pictures: 64 NC, 148 CC, and 12 AS events

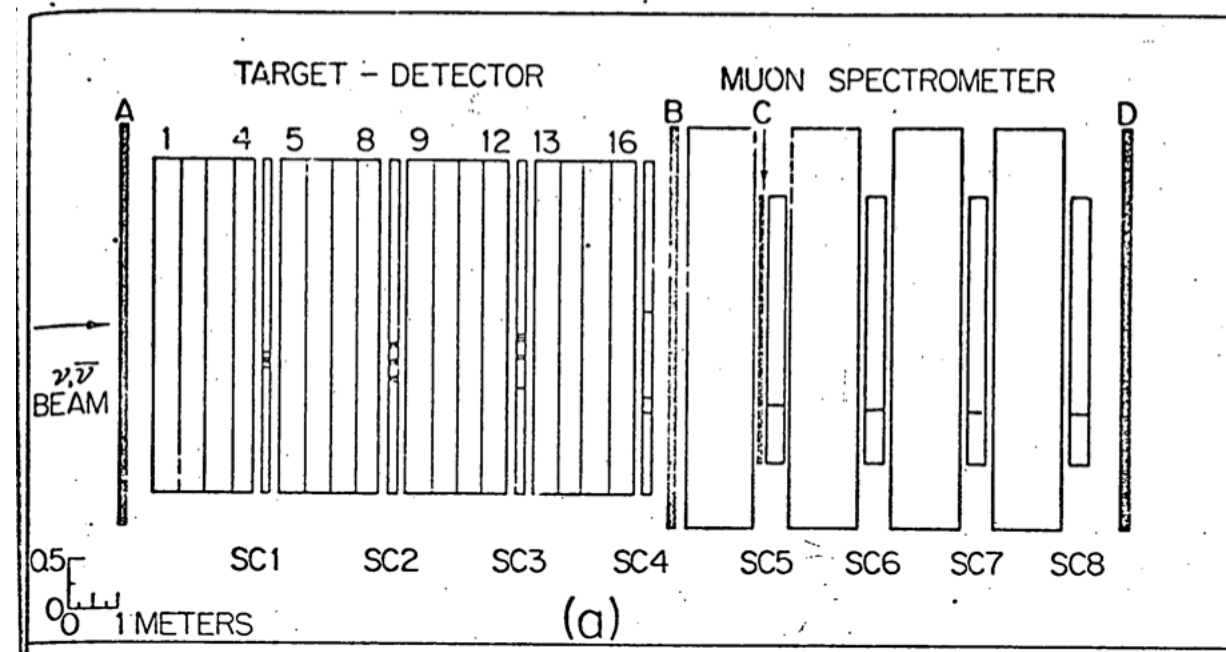
Gargamelle 1973- Results

- $\left(\frac{NC}{CC}\right)_\nu = 0.21 \pm 0.03$
- $\left(\frac{NC}{CC}\right)_{\bar{\nu}} = 0.45 \pm 0.09$
- They conclude by remarking that these ratios are consistent with a value of $\sin^2 \theta_w$ between 0.3 and 0.4
 - This is a bit off the true value



Fermilab HPW 1973

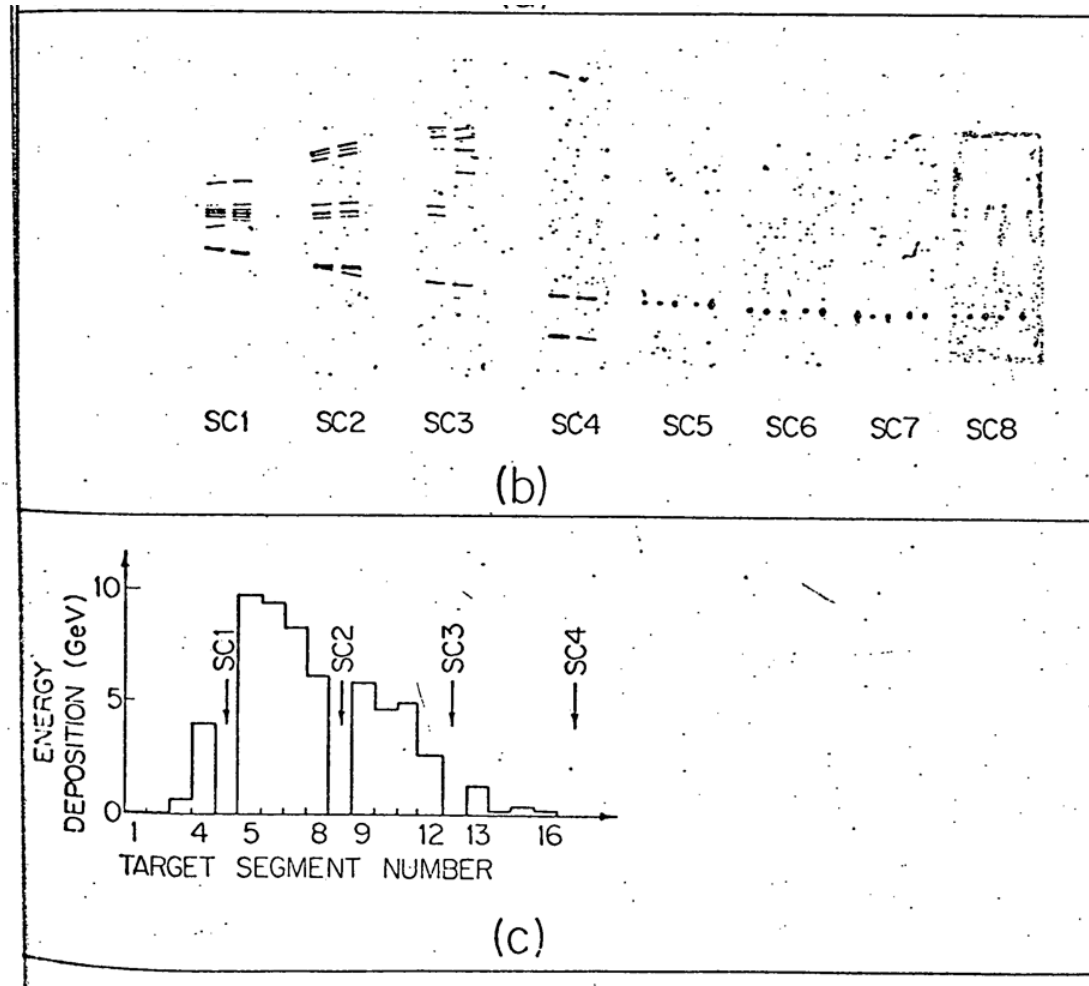
- “HPW” meaning a group from Harvard, Penn, and Wisconsin
- NOT a bubble chamber experiment
- Detector is liquid scintillator (1-16) with spark chambers (SC1-4) interspersed
- Muon spectrometer is 4 toroidal iron magnets with spark chambers (SC5-8) after them



The little lines in the spark chambers are meant to be a depiction of an event

Fermilab HPW 1973

- Interaction vertices are determined by the distribution of energy deposits and by extrapolation of spark chamber tracks



This is what a typical inelastic neutrino event with muon would look like
It's a zoom-in of the little lines from the previous slide

Fermilab HPW 1973

- The main difficulty here was accounting for muon acceptance.
- They needed to know what fraction of events didn't have a muon because it was an NC event, and what fraction didn't have a muon because the muon just fell out of the detector acceptance (UME)
- I, II, and III all involve different cuts on the allowed angles of tracks closest to the vertex (I is most accepting, III least accepting)

TABLE I. Summary of analyses. (I) Analysis of totality of events (II) Analysis with angular requirements in one plane (III) Analysis with angular requirements in both planes

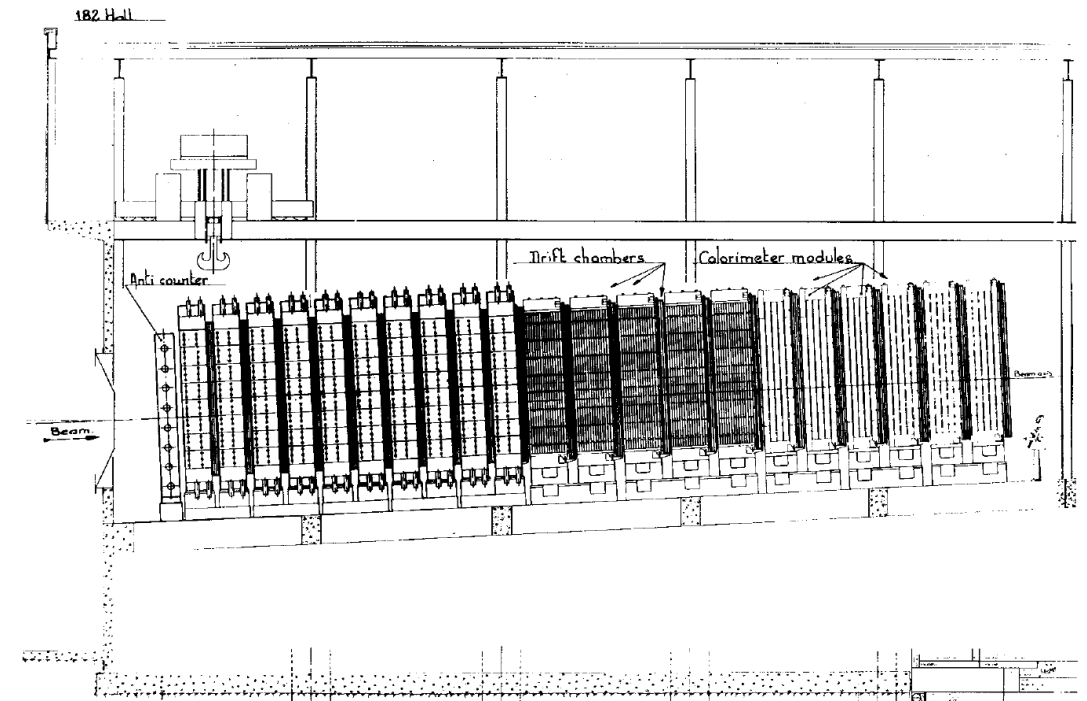
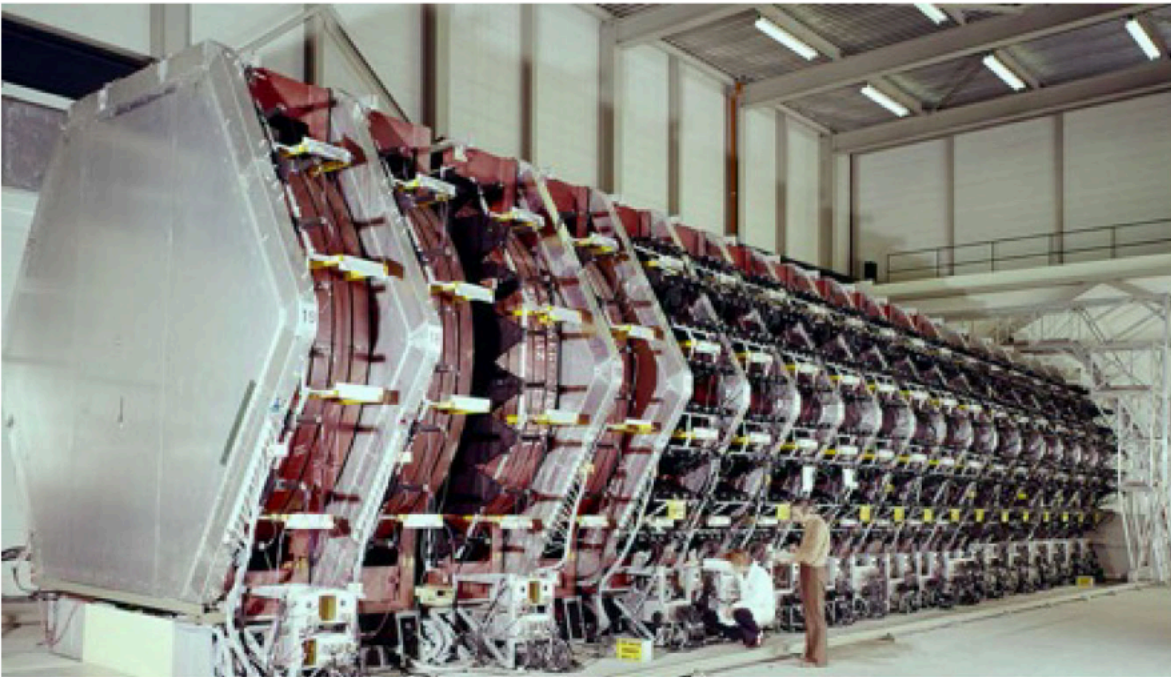
Target segments	Proton energy (GeV)	Visible muon events	No visible muon (1)	UME	Excess muonless events (2)	Purity of sample (2)/(1)	Statistical significance of effect s.dev.	Ratio of cross-sections R
I 1-6	300	52	59	41	18	25%	2.1	0.20 ± 0.12
	400	27	23	20	3		0.5	0.06 ± 0.14
	7-12	72	53	28	25	50%	4.0	0.25 ± 0.10
		21	23	10	13		3.3	0.42 ± 0.23
	7-12	300 + 400 combined	93	76	38	50%	5.2	0.29 ± 0.09
	7-12	300 + 400 combined	93	76	38	50%	5.2	0.29 ± 0.09
II 1-12	300	56	54	24	30	56%	5.1	0.29 ± 0.10
III 1-12	300	13	11	1.9	9.1	83%	6.7	0.39 ± 0.19

They didn't publish a value for $\sin^2 \theta_w$, and they didn't publish their ratios of neutrino and antineutrino events. This was more of a confirmation that NC events are real

There was a similar experiment by a Fermilab-CalTech collaboration in 1975

CERN lighting round- CDHS (1977)

- Electronic detector (like Fermilab setup)
 - Magnetized iron plates interleaved with scintillators + drift chambers for muons
- Used higher energy protons from SPS at CERN (better muon tagging)



CERN lighting round- CDHS (1977)

Table 1

Data reduction for the ratio of neutral to charged current inclusive cross-sections for $E_H > 12$ GeV

	Neutrinos	Antineutrinos
NC candidates	10770 ± 104	3314 ± 58
Cosmic-ray background	-59 ± 7	-119 ± 10
WBB background	-286 ± 126	-646 ± 116
CC background	-1493 ± 64	-235 ± 49
NC with $L < 16$ and $L > L_{\text{cut}}$	$+150$	$+43$
K_{e3} correction	-1008	-154
NC signal	8074 ± 156	2203 ± 130
CC candidates	26509 ± 163	6483 ± 81
WBB background	-239 ± 117	-323 ± 83
CC extrapolation	$+1467 \pm 64$	$+253 \pm 42$
NC with $L > L_{\text{cut}}$	-134	-35
CC signal	27603 ± 211	6378 ± 123
NC/CC (error only statistical)	0.293 ± 0.006	0.346 ± 0.021
NC/CC (final result, systematic error included)	0.293 ± 0.010	0.35 ± 0.03

Accurate measurement of NC/CC ratios!

Measured $\sin^2 \theta_w = 0.24 \pm 0.02$

(By 1986 refined to $\sin^2 \theta_w = 0.225 \pm 0.005 \pm 0.003$)

CERN lighting round- CHARM

- Also an electronic detector at SPS
- Placed downstream from CDHS
 - Better resolution than CDHS but smaller fiducial region
- Best measurement was in 1984:
 $\sin^2 \theta_w = 0.236 \pm 0.005 \pm 0.003$
- Also managed to measure NC and CC neutrino scattering off of electrons: $\sin^2 \theta_w = 0.211 \pm 0.047$

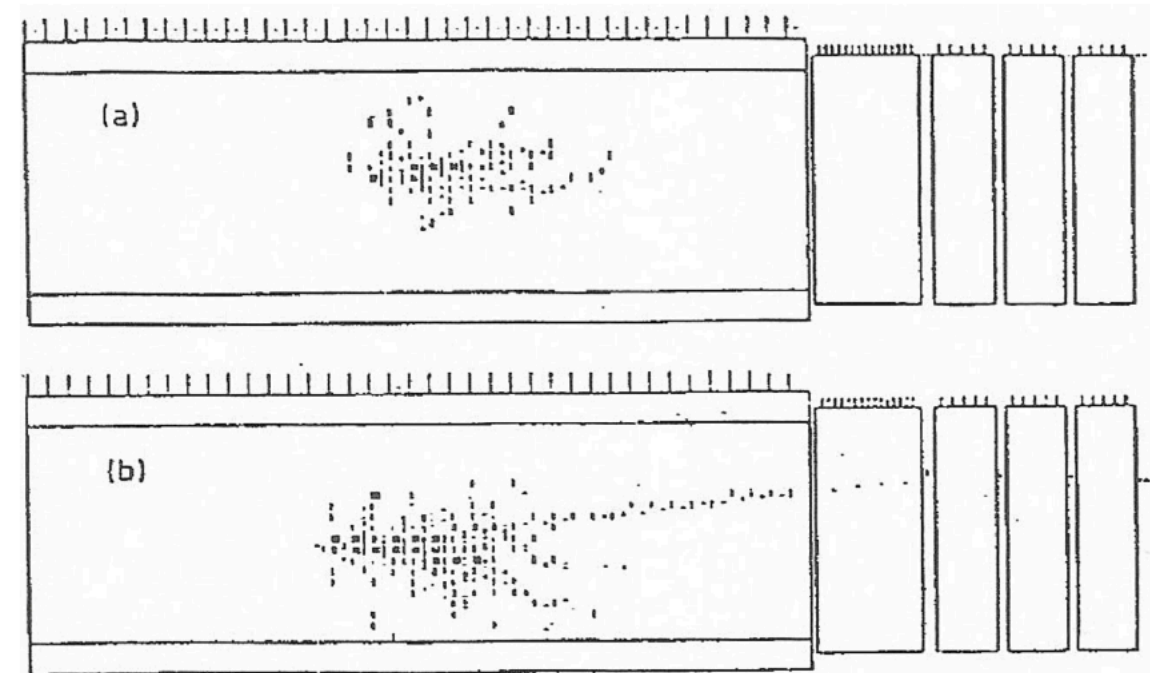
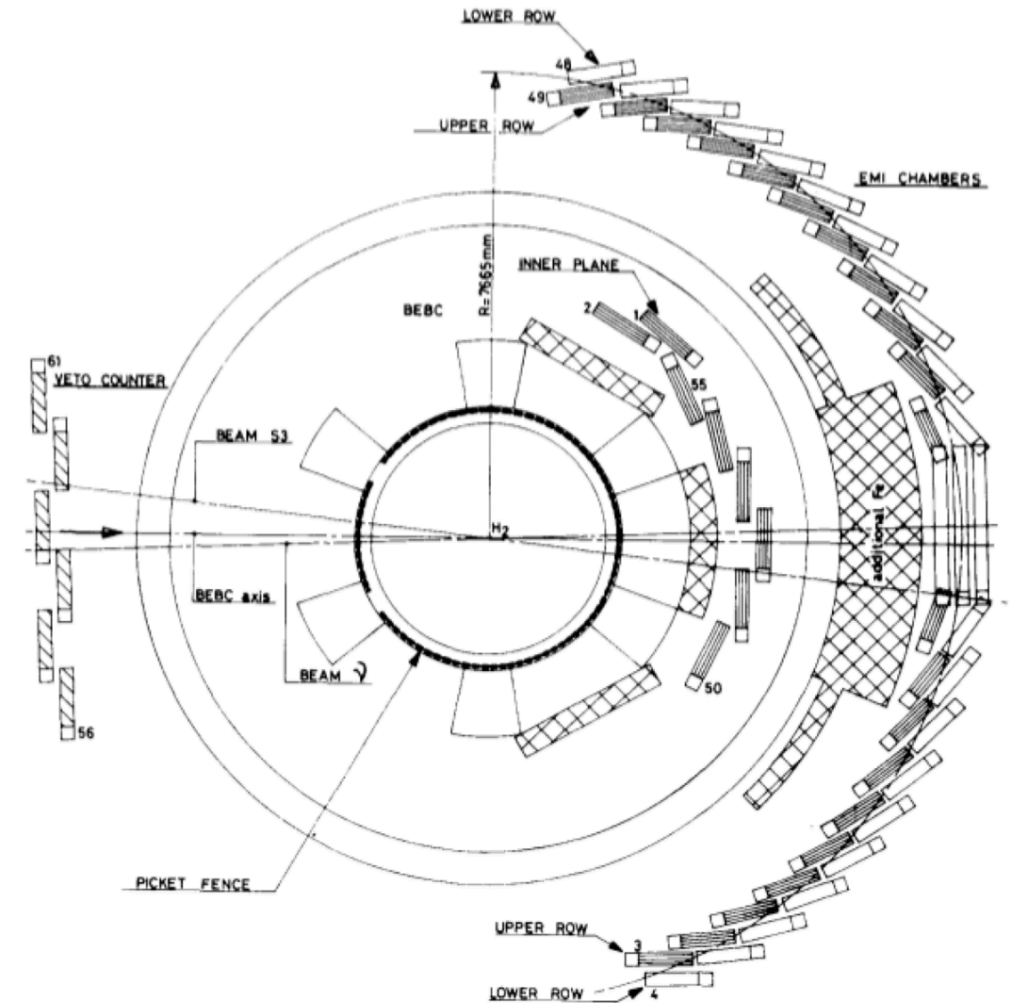


Illustration of NC (a) and CC (b) events as detected by CHARM

CERN lighting round- BEBC (Big European Bubble Chamber)

- Hybrid detector using SPS neutrinos
- Used external and internal muon detectors
- Best measurement from 1986:
 $\sin^2 \theta_w = 0.240 \pm 0.030$



Part III: Left-right asymmetry in electron-deuterium scattering

Why asymmetry?

- DINS looked for a difference between NC and CC cross sections
- Asymmetry measurements look for interference between an electromagnetic amplitude and the neutral weak current
- A SLAC experiment from 1978 aimed to measure

$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

- Electroweak theory tells us:

$$A = \frac{-G_F Q^2}{2\sqrt{2}\pi\alpha} \frac{9}{10} \left\{ 1 - \frac{20}{9} \sin^2 \theta_w + (1 - 4 \sin^2 \theta_w) \left[\frac{1 - (1 - y)^2}{1 + (1 - y)^2} \right] \right\}$$

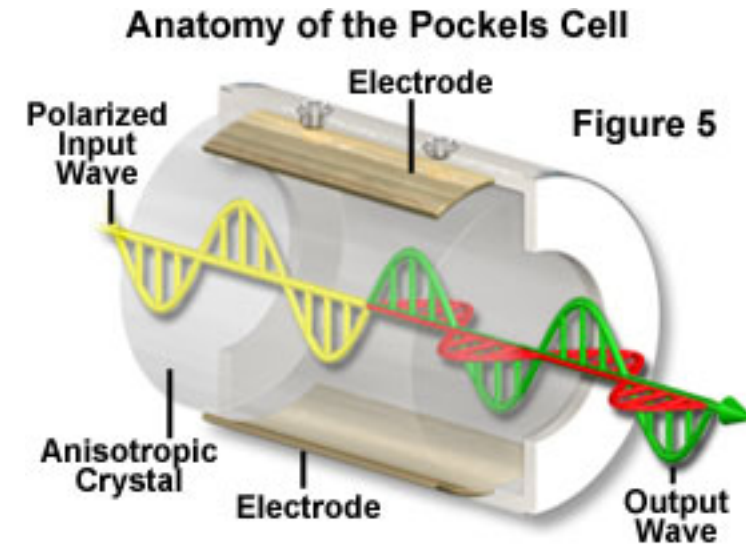
Where y is the fractional electron energy loss: $y = \frac{E - E'}{E}$

- To make a statistically significant measurement, you'll want $\sim 10^{10}$ events

(Previous experiments hadn't had enough stats to see this)

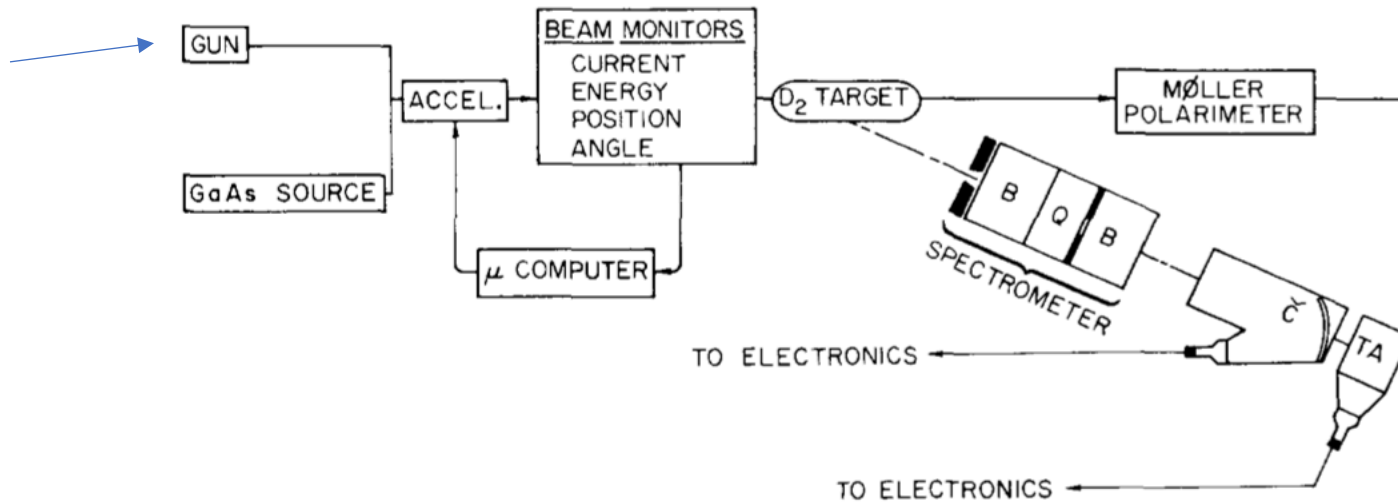
SLAC 1978- Experimental specifics

- How to make an intense source of longitudinally polarized electrons:
 - Gallium Arsenide (GaAs) crystal serves as electron source- you optically pump the crystal between the valence and conduction bands with circularly polarized photons
 - Crystal surface is treated so that the electrons don't depolarize
 - Photons come from a laser that is pulsed to match the LinAc (120 pulses/sec)
 - Linearly polarized light from laser is made circular with Pockels cell
 - Plane of light polarization incident on Pockels cell can be changed by reorienting a prism
 - The pulse driving the Pockels cell was switched randomly, meaning that the electron polarization was random
 - Achieved average polarization, $|P_e|$, of 0.37



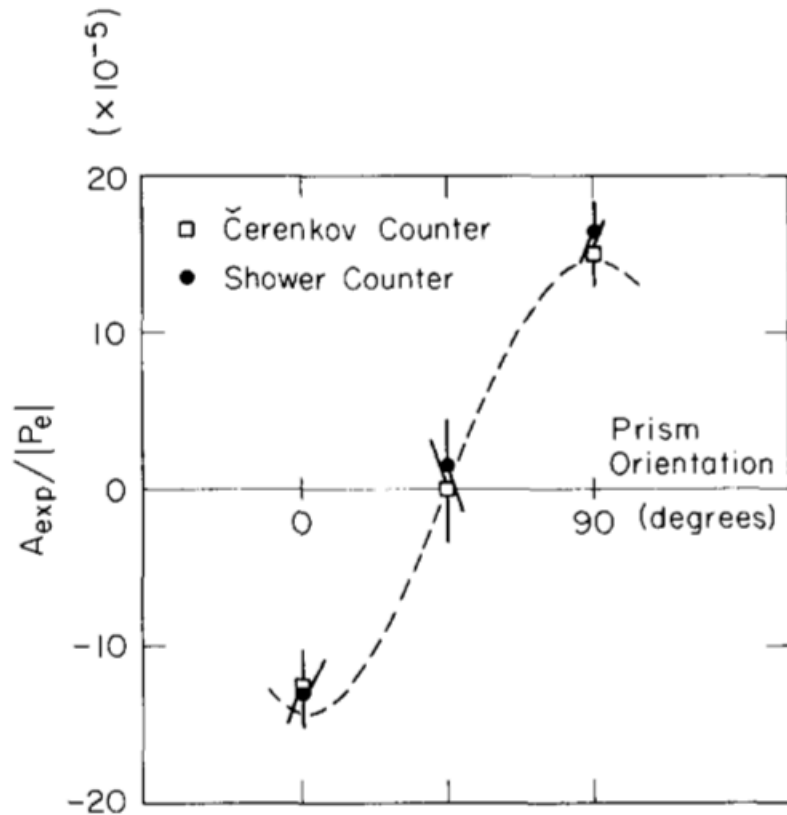
SLAC 1978- Experimental specifics

Used to check
asymmetry when using
an unpolarized beam

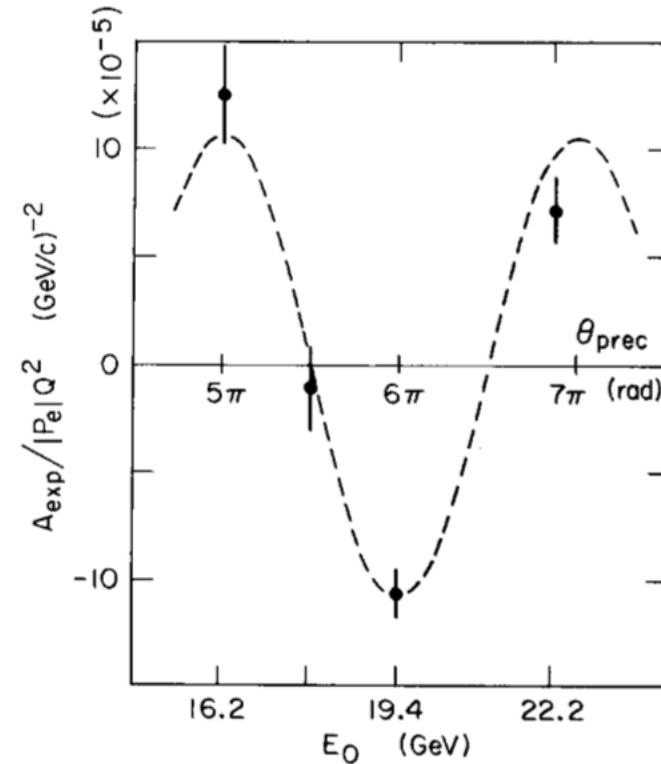


- Target is 30cm cell of liquid deuterium
- Spectrometer positioned at scattering angle of 4° , optimized for electron energy loss of about 20% from beam energy
- Rather than count individual electrons, they integrated the outputs of each phototube
- Significant work had to be done to verify that beam conditions were the same for both settings of polarization (using the beam monitors)

SLAC 1978- Results



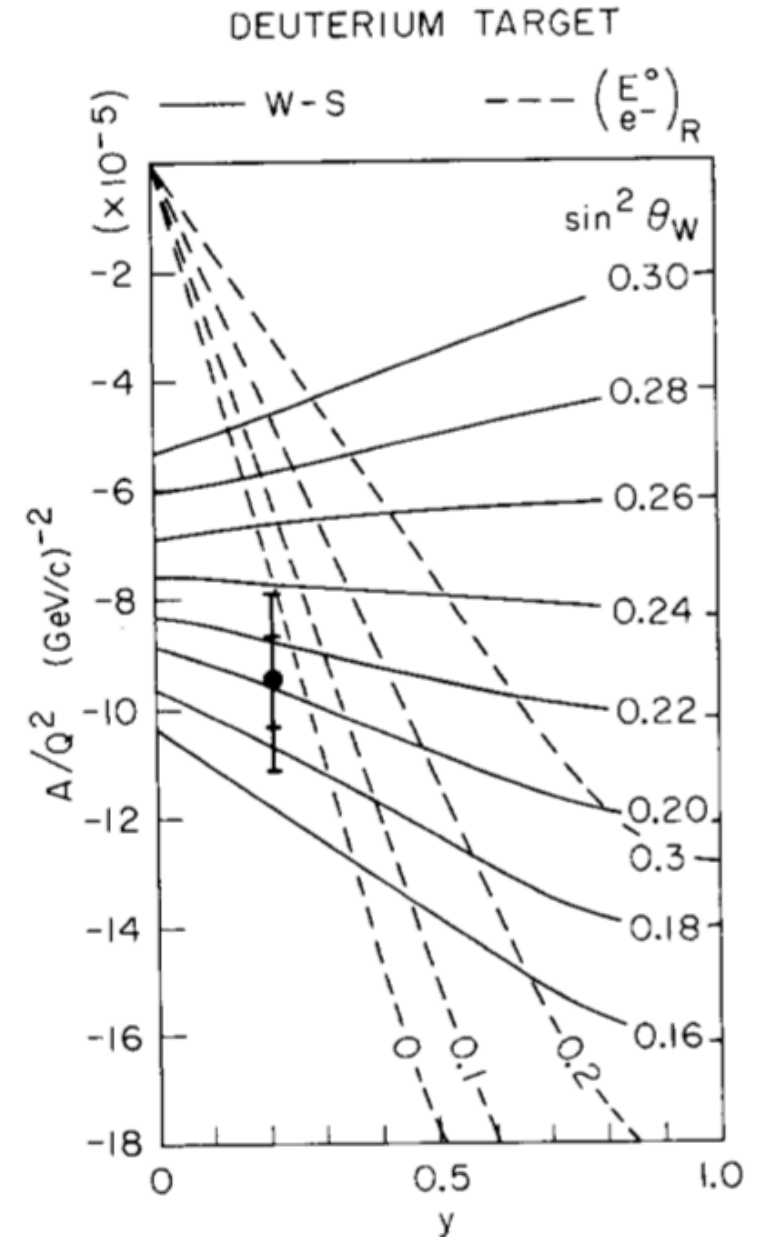
The prism orientation affects electron polarization. Middle point is unpolarized. Left and right points are oppositely polarized.



They had to account for the precession of the electron helicity in the transport magnets, which depended on the beam energy. So asymmetry depended on beam energy

SLAC 1978- Results

- Measured $\sin^2 \theta_w = 0.20 \pm 0.03$
- Ruled out some models that had left-right symmetry (in particular, people had tried to explain the DINS results as a consequence of different neutrino and anti-neutrino handedness alone)



Conclusions

- Glashow, Weinberg, and Salam shared the 1979 Nobel for contributions to Electroweak unification
- Carlo Rubbia, who was an author on the Fermilab experiment, shared the Nobel prize in 1984 with Simon van der Meer for discovering the W and Z bosons
 - Thanks to the measurements of $\sin^2 \theta_w$ (of about 0.23), it had been approximated that the W mass should be about 80 GeV, and the Z should be about 91 GeV
- Very precise measurements of $\sin^2 \theta_w$ were made at LEP using forward backward asymmetry in $e^+ e^-$ scattering
- PDG currently quotes: $\sin^2 \theta_w (M_Z) = 0.23122(15)$

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